PATENT

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APPLICATION FOR UNITED STATES LETTERS PATENT

for

REMOTE SENSING DEVICE TO DETECT MATERIALS OF VARYING ATOMIC NUMBERS

by

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This application claims priority to, and incorporates by reference, U.S. Provisional Patent Application Serial No. 60/428,165 which was filed November 21, 2002.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates generally to the field of inspection systems. More particularly, the invention relates to a remote sensing device to detect materials of varying atomic numbers.

2. Discussion of the Related Art

The identification of weapons-grade materials (such as uranium, plutonium, or radiation dispersion devices known as "dirty bombs") concealed within cargo containers is of growing importance worldwide.

Typically, instruments such as Geiger counters and gamma ray detectors are employed at ports-of-entry to scan such containers. Nevertheless, these technologies have limited applications. For example, highly-enriched uranium (^{235}U) does not emit a significant flux of gamma rays, and can be easily shielded by a thin layer of lead.

Meanwhile, it is known that by measuring photon attenuation, one can identify materials with large atomic numbers. In order to accurately interrogate a cargo container, a high-energy beam of photons with high penetrating power may be used. Further, a detection system that can identify materials of varying atomic number is needed.

Until now, the requirements of a method and/or apparatus for probing closed containers for weapons-grade fissile materials of varying atomic number with a high-

energy photon beam, and resolving the energy and attenuation of the outgoing flux of photons from the container has not been met.

SUMMARY OF THE INVENTION

There is a need for the following embodiments. Of course, the invention is not limited to these embodiments.

According to an aspect of the invention, a method for identifying a material includes casting an incident photon beam on the material and detecting an emerging photon beam with an array of fission-fragment detectors, a first set of scintillator paddles, and a second set of scintillator paddles, wherein the array of fission-fragment detectors, the first set of scintillator paddles, and the second set of scintillator paddles are sensitive to different ranges of photon beam energy.

According to another aspect of the invention, a photon beam flux monitor for resolving a high-energy beam includes an array of fission-fragment detectors for measuring a first range of photon energies, a first set of scintillator paddles coupled to the array of fission-fragment detectors for measuring a second range of photon energies, a convertor coupled to the first set of scintillator paddles, and a second set of scintillator paddles coupled to the convertor for measuring a third range of photon energies.

These, and other, embodiments of the invention will be better appreciated and understood when considered in conjunction with the following description and the accompanying drawings. It should be understood, however, that the following

description, while indicating various embodiments of the invention and numerous specific details thereof, is given by way of illustration and not of limitation. Many substitutions, modifications, additions and/or rearrangements may be made within the scope of the invention without departing from the spirit thereof, and the invention includes all such substitutions, modifications, additions and/or rearrangements.

BRIEF DESCRIPTION OF THE DRAWINGS

The drawings accompanying and forming part of this specification are included to depict certain aspects of the invention. A clearer conception of the invention, and of the components and operation of systems provided with the invention, will become more readily apparent by referring to the exemplary, and therefore nonlimiting, embodiments illustrated in the drawings, wherein like reference numerals (if they occur in more than one view) designate the same or similar elements. The invention may be better understood by reference to one or more of these drawings in combination with the description presented herein. It should be noted that the features illustrated in the drawings are not necessarily drawn to scale.

FIG. 1 is a block diagram of a photon interrogation system, representing an embodiment of the invention.

FIG. 2 is a diagram of a fission-fragment detector, representing an embodiment of the invention.

FIG. 3 is an exploded view of the fission-fragment detector, representing an embodiment of the invention.

FIG. 4 is a diagram of an array of fission-fragment detectors, representing an embodiment of the invention.

FIG. 5 is a block diagram of a data acquisition and processing system, representing an embodiment of the invention.

FIG. 6 is a simulated photon energy distribution curve, illustrating an embodiment of the invention.

DETAILED DESCRIPTION

The invention and the various features and advantageous details thereof are explained more fully with reference to the nonlimiting embodiments that are illustrated in the accompanying drawings and detailed in the following description. It should be understood that the detailed description and the specific examples, while indicating specific embodiments of the invention, are given by way of illustration only and not by way of limitation. Various substitutions, modifications, additions and/or rearrangements within the spirit and/or scope of the underlying inventive concept will become apparent to those of ordinary skill in the art from this disclosure.

The invention includes a method and/or apparatus for identifying the presence of substances concealed in closed containers or inaccessible areas by using a beam of high-energy X-rays produced from an electron accelerator. The invention also includes a

method and/or apparatus for measuring fluxes of transmitted photons in the regime of high energies, thereby determining the atomic number of the material on the photon beam path. Further, the invention can include an energy-sensitive photon beam flux monitor (BFM) to analyze properties of materials by measuring the energy-dependent attenuation of the transmitted beam of photons.

In the passage of photons through matter, a photon interacts with atoms or nuclei in an energy-dependent way. Specifically, high atomic number (Z) materials tend to absorb higher energy photons, and low Z materials tend to absorb lower energy photons. The invention includes a method and/or apparatus for measuring the attenuation of a photon beam flux, therefore yielding a measure of the density and distribution of the interrogated material. The invention may be used to identify and distinguish high and low density materials concealed within a vessel, including weapons-grade materials such as, for example, uranium, plutonium, or radiation dispersion devices (known as "dirty bombs"). Further, the invention can include using a detector with a natural uranium target to measure the fission fragments induced from photons. In one embodiment, the detector has a high degree of photon-energy selectivity in the range of 10.0 to 20.0 MeV. In another embodiment, the invention includes a photon beam flux monitor including a detector for resolving photon energies up to about 6 MeV and another detector for resolving fission-fragment energies above about 6 MeV. In yet another embodiment, the invention includes using three detectors, each detector being sensitive to a different range of energies. These energy ranges may overlap.

Referring to **FIG. 1**, a block diagram of a photon interrogation system **100** is depicted, representing an embodiment of the invention. An electron beam generator (accelerator) **105** directs a beam upon a radiator **110** to produce a photon beam through the process of bremsstrahlung. In one embodiment, the electron beam generator **105** produces a flux of about 10^7 photons per second. In another embodiment, the electron beam generator **105** produces a photon beam with energies between about 1 to 15 MeV. The radiator **110** may be, for example, a thin tungsten foil. The radiator **110** is coupled to an electron stopping block **115**, which interrogates a cargo container **125** with an incident photon beam **120**. A emerging photon beam **121** is monitored with a photon beam flux monitor **130**.

Still referring to **FIG. 1**, the photon beam flux monitor **130** includes three detection devices including an array of fission-fragment detectors (Parallel-Plate Avalanche Detectors or PPADs) **135** followed by two sets of scintillator paddles (telescopes) **140** and **150** with a convertor **145** in between, wherein each scintillator is sensitive to a different range of photon energies. In one embodiment, the convertor **145** is a lead (Pb) convertor. The first set of scintillator paddles **140** may detect materials of low atomic number (low Z) by resolving fission-fragment energies up to about 6 MeV, and the second set of scintillator paddles **150** may detect materials of high atomic number (high Z) by resolving photon energies exceeding about 6 MeV. In other embodiments, different energy ranges may be desirable.

Depending upon complementary detection techniques and the desired penetration power of the photon beam **120**, the electron beam energies of the emerging photon beam

121 may be as high as 50 MeV, and its energy distribution may range between 0 and 50 MeV with a characteristic $1/E\gamma$ falloff (bremsstrahlung photons).

Still referring to **FIG. 1**, the three sets of detectors **135**, **140** and **150** can be used to measure the beam of photons **121** emerging from the cargo container **125**. By resolving the energy of the beam **121**, the effective density distribution of the matter within the container **125** may be revealed. Material concealed within the cargo container **125** may selectively absorb the various parts of the bremsstrahlung spectrum of the incident photon beam **120** depending upon its atomic number. The photon flux monitor **130** may register a drop in the emerging photon beam **121** intensity in the energy regime where the interrogated material has preferentially absorbed the photon beam.

Still referring to **FIG. 1**, in one embodiment, low-Z detectors may be formed of a telescoping array of approximately 1 inch thick scintillator paddles **140**, wherein a first layer blocks out charged particles. Each scintillator paddle may be instrumented on one end with a photomultiplier tube (PMT). The low-Z detector array may be segmented to minimize pile up of the signal. Low-Z materials such as water, chemical explosives, and plastic interact primarily with the lower energy portion of the emerging photon beam **121**. The variation of the PMT current may give a measurement of the distribution of low-Z materials within the interrogated vessel **125**. In one embodiment the scintillator paddles **140** are sensitive to photon energies less than about 6 MeV. In other embodiments, different energy ranges may be desirable.

Still referring to **FIG. 1**, high-Z detectors may be formed of a grouping of thin scintillator paddles **150**. Placed in front of these scintillators may be a thin lead-convertor

foil **145** for producing electron/positron (e-/e+) pairs. When a photon strikes the convertor **145** (which may be, for example, a tungsten or lead foil), the photon converts into the electron/positron pair. In one embodiment, the thickness of the convertor **145** is between about 1% to 5% radiation lengths. Next, the electron and positron travel into the second set of scintillators **150**, where they are detected. The e-/e+ pairs may be measured, for example, by placing a sweeping dipole magnet (not shown) in between the convertor **145** and a bilaterally-symmetric arrangement of the scintillator paddles **150**. The e-/e+ pairs may also be measured by directly measuring the double ionization peak. In one embodiment, the scintillator paddles **150** are sensitive to photon energies exceeding about 6 MeV. In other embodiments, different energy ranges may be desirable.

Still referring to **FIG. 1**, the array of fission-fragment detectors (PPADs) **135** may be ionization detectors that operate in the avalanche regime, which is defined by a combination of gas pressure and electric field such that a single free electron can start an exponential ionization process. Typical gas pressures vary from 1 Torr to about 25 Torr, while the corresponding electric field varies from about 100 V/mm to 400 V/mm. The array of fission-fragment detectors **135** may be tuned to the photofission cross section of the fissile material to be interrogated in container **125**. In one embodiment, the array of fission-fragment detectors **135** is sensitive to photon energies in the range of about 10 to 20 MeV. In other embodiments, a different range of energies may be desirable.

Referring to **FIG. 2**, a diagram of fission-fragment detector **200** (PPAD) is depicted according to one embodiment of the invention. The fission-fragment detector **200** may be used as an element of the array of fission-fragment detectors **135** detailed in

FIG. 1. The fission-fragment detector **200** is a two-parallel-plate capacitor immersed in a gas at low pressure. A voltage is applied between the plates to establish the conditions for an avalanche regime to be generated across the gap. When a free electron is created inside the detector by an ionizing particle, it generates an avalanche of electron pairs. The number of avalanche electrons is proportional to the distance they travel. In order to minimize the probability of electric breakdown in the form of sparks and glow discharges when the PPAD **200** is in the avalanche regime, a gas with high self-quenching properties may be used such as, for example, isobutane.

Referring to **FIG. 3**, an exploded view of the fission-fragment detector **200** detailed in **FIG. 2** is depicted according to one sample embodiment of the invention. A target holder **205** including a photofission target **210** is coupled to a collimator **235**. The collimator is coupled to an anode plane **215**, and the anode plane **215** is coupled to a cathode plane **230**. The anode plane **215** includes a grid of gold-plated tungsten/rhenium wires **220**, and the cathode plane **230** includes an aluminized mylar foil **225**. Both electrodes (anode **215** and cathode **230**) may include rectangular frames of PC-Board material (such as fiberglass), with windows cut inside. The thickness of each frame may be approximately 1.5 mm, so that when placed back to back, they generate a gap between the electrodes **215** and **230** of approximately 3 mm. Part of the copper on the external side of the PC boards may be removed to provide space for connecting resistors, capacitors, high-voltage (HV) connectors, and signal connectors. The copper may also be removed from the edges of the windows to minimize the probability of electric breakdown along the limits of the active region. In order to further reduce the probability

of electric breakdown, the cathode **230** window may be made approximately 10 mm x 10 mm larger in area than the anode **215** window.

Still referring to **FIG. 3**, the grid wires **220** may be attached to the anode frame **225** with epoxy glue. Exposed areas are covered with a layer of epoxy glue, and the high voltage connectors are encapsulated in plastic cases. The PPAD **200** may be tuned to uranium by having the target **210** made of, for example, a thin film of ^{238}U deposited on one side of an approximately 100 pm thick aluminum foil. The target **210** may also be, for example, an approximately 178 micron thick film of ^{238}U. In one embodiment, the invention includes using targets **210** of different materials to tune the PPAD **200** to a corresponding range of energies. The ability to tune the PPAD **200** allows detection of materials of varying atomic numbers.

Still referring to **FIG. 3**, fission fragments are generally slow moving and have high charge, hence they may be readily stopped within thick targets. Typically, only fission fragments produced from the outer 5-um layer of the target **210** emerge, and the rest is absorbed within the target **210**. Thick targets **210** may serve as a relative flux monitor, since the rate of photofission production in the outer layer scale with the intensity of the beam. The absolute flux can be calibrated with an empty vessel. In one embodiment, an absolute measurement may be made by having thin films of ^{238}U sputtered onto an aluminum substrate.

Still referring to **FIG. 3**, the target **210** is sandwiched between two frames with approximately 5 mm x 10 mm windows and may be connected to the electrodes **215** and **230** by teflon screws, where the distance between the targets and the detectors is set by

teflon spacers. The angles of the particles coming into the detectors electrodes **215** and **230** are constrained by the collimator **235**. The collimator **235** may be made of fiberglass, approximately 1 mm thick, with a circular hole (approximately 40 mm in diameter) in the center.

Referring to **FIG. 4**, a diagram of an array of fission-fragment detectors **400** (PPADs) is depicted according to one aspect of the invention. The array of fission-fragment detectors **400** may be used as the array **135** of **FIG. 1**. A pair of collimators **405** is coupled to a target surface **410** and to a fission-fragment detector **415** (PPAD). The PPAD **415** is coupled to a rail **420** through a holder **425**. In one embodiment, the array of fission-fragment detectors **400** includes a plurality of target-detector assemblies.

Still referring to **FIG. 4**, the array of fission-fragment detectors **400** may be operated in a low-pressure gas atmosphere such as, for example, isobutane, and placed inside a hermetically sealed reaction chamber. In one embodiment, in order to maintain the avalanche regime and to keep the gain of avalanche detectors constant, the pressure and purity of the gas is maintained stable by flowing the gas through the chamber using a pressure and flow control system.

Referring to **FIG. 5**, a block diagram of a data acquisition and processing system **500** is depicted according to one exemplary embodiment of the invention. The data acquisition and processing system **500** may be used to read and process a signal from a detector (**135, 140,** or **150**), detailed in **FIG. 1**.

Still referring to **FIG. 5**, a detection device signal is amplified by a pre amp circuit **505**. A quad linear fan-in fan-out circuit **510** takes the amplified device signal and

generates four identical output signals with unit gain, while providing control over the polarity of these output signals. The quad linear fan-in fan-out circuit **510** is coupled to a time-to-digital converter circuit **515**, an analog-to-digital converter circuit **520**, and to a discriminator circuit **525**. The discriminator circuit **525** outputs a digital NIM (nuclear instrumentation module) pulse when its input is above a threshold. In another embodiment, the discriminator circuit **525** outputs Fastbus pulses. The discriminator **525** is coupled to a scaler circuit **535** and to the first input of an AND gate **530**.

Still referring to **FIG. 5**, an accelerator signal, indicating whether the beam generator **105** detailed in **FIG. 1** is in operation, is coupled to the second input of the AND gate **530**. The output of the AND gate **530** is coupled to the analog-to-digital converter **520**, the time-to-digital converter **515**, and to the scaler circuit **535**. The time-to-digital converter circuit **515**, the analog-to-digital converter circuit **520**, and the scaler circuit **535** are coupled to a standard bus backplane **540**. In one embodiment, the backplane **540** is a VME (Versa Module Europe) backplane. The backplane **540** is coupled to a computer **545** including a data acquisition system board or system. The computer **545** is coupled to a program storage media **550**. The program storage media **550** may be any type of readable memory including, for example, a magnetic or optical media such as a card, tape or disk, a semiconductor memory such as a PROM or FLASH memory, or any other available media.

In one embodiment, three readout logic circuits such as the one detailed in **FIG. 5** may be used to process each signal from the three detectors **135**, **140**, and **150** detailed in **FIG. 1**. The data acquisition system **500** may be used to collect signals from each device

of the photon interrogation system **100**. Each of the three measurements can be buffered with an identification tag at the backplane **540** and read out with data acquisition software stored at the program storage media **550** and used by the computer **545**. The three measurements may be combined to create, for example, a histogram or an energy distribution graph.

Referring to **FIG. 6**, a simulated photon energy distribution graph **600** of the bremsstrahlung spectra resulting from the interaction of the electron beam directed upon the radiator is plotted on a log-log scale. The horizontal axis is the photon energy in MeV and the vertical axis is the photon yield binned in units of dN/dEgamma. This photon energy distribution result can be obtained by a data acquisition system such as the one depicted in **FIG. 5** when the container **125** detailed in **FIG. 1** is absent.

Referring to **FIGS. 1** and **6**, The graph **600** is created by combining a low-Z detector **140** signal **605**, a PPADs detector **135** signal **610**, and a high-Z detector **150** signal **615**. In the presence of a radiological device composed of, for example, uranium, plutonium or neptunium concealed within the interrogated vessel **125**, the measured spectrum from the beam flux monitor **130** reflects a precipitous drop in intensity between about 10 and 20 MeV. The radiological material selectively absorbs the photon beam within its energy regime.

The terms a or an, as used herein, are defined as one or more than one. The term plurality, as used herein, is defined as two or more than two. The term another, as used herein, is defined as at least a second or more. The terms including and/or having, as used herein, are defined as comprising (i.e., open language). The term coupled, as used

herein, is defined as connected, although not necessarily directly, and not necessarily mechanically. The term approximately, as used herein, is defined as at least close to a given value (e.g., preferably within 10% of, more preferably within 1% of, and most preferably within 0.1% of). The term program or software, as used herein, is defined as a sequence of instructions designed for execution on a computer system. A program, or computer program, may include a subroutine, a function, a procedure, an object method, an object implementation, an executable application, an applet, a servlet, a source code, an object code, a shared library/dynamic load library and/or other sequence of instructions designed for execution on a computer system.

The appended claims are not to be interpreted as including means-plus-function limitations, unless such a limitation is explicitly recited in a given claim using the phrase(s) “means for” and/or "step for." Subgeneric embodiments of the invention are delineated by the appended independent claims and their equivalents. Specific embodiments of the invention are differentiated by the appended dependent claims and their equivalents.